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Climate change and water productivity

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Abstract

Over the last three decades, climate change has emerged as one of the most crucial issues for humankind, with serious implications for sustainable development. In recent decades, changes in climate have caused the impacts on natural and human systems on all continents and across the oceans. Human activities are estimated to have caused approximately 1.0°C of global warming above pre-industrial levels, with a likely range of 0.8°C to 1.2°C. Global warming is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate. Climate change increases variability in the water cycle, inducing extreme weather events such as droughts and more erratic storms, reducing the predictability of water availability, affecting water quality and threatening sustainable development and biodiversity worldwide. Agriculture is the sector most vulnerable to climate change due to its high dependence on climate and weather. It is important to determine the impacts of climate change on water resources in order to develop possible adaptation strategies to improve water productivity. This paper discusses the observed climate change over the past few decades; the climate change-induced impacts, such as rising sea levels, changing rainfall patterns, increased droughts, and more erratic storms; the future climate change; the climate change impacts on water productivity; and the strategies to improve the water productivity such as improved policies, emphasis on sustainability, improving water resource management and use of appropriate models.

Keywords: Climate Change; Sustainable Development; Water Availability; Water Productivity; Water Resources Management

INTRODUCTION

Earth's climate system is controlled by a complex set of interactions among the atmosphere, oceans, continents and living systems. The United Nations Framework Convention on Climate Change (UNFCCC), in its Article 1, defined climate change as: 'a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods'. Evidence is pointing to the fact that human-driven changes in Earth's energy balance are driving a warmer and wetter atmosphere, with this trend superimposed on and magnifying natural variability. Over the last three decades, climate change has emerged as one of the most crucial issues for humankind, with serious implications for sustainable development.

The Intergovernmental Panel on Climate Change (IPCC), is the leading international body for the assessment of climate change, established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) in 1988, to provide the world with a clear scientific view on the current state of knowledge in climate change and its potential environmental and socio-economic

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impacts. Governments participate in the review process and the plenary Sessions, where main decisions about the IPCC work programme are taken and reports are accepted, adopted, and approved. According to the Fifth Assessment Report of the WMO/UNEP Intergovernmental Panel on Climate Change (IPCC), each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850 (IPCC, 2013). The globally averaged combined land and ocean surface temperature data as calculated by a linear trend, show a warming of 0.85 ˚C over the period 1880 to 2012. More frequent and intense extreme weather events and increasing uncertainty in rainy season patterns are already having the significant impacts on food production, food distribution infrastructure, livelihood assets, human health and food emergencies, in both rural and urban areas (FAO, 2008).

Rapidly rising population growth and diminishing arable land, particularly in the developing countries, has increased the stress on the natural resource base. Lal (1991) calculated that the per capita arable land will progressively decline from about 0.3ha in 1990 to 0.23ha by the year 2000, 0.15ha by 2050 and 0.14ha by 2100. Combined with the growing concerns regarding the decline in the non-renewable sources of energy and the degradation of environment, it is certainly timely that the world is taking a hard look at the way agricultural adaptation to climate change and improved sustainability.

In this article, there is a description of how climate change increases variability in the water cycle, inducing extreme weather events such as droughts and more erratic storms, reducing the predictability of water availability, affecting water quality and threatening sustainable development and biodiversity worldwide. The strategies to improve the water productivity are described.

OBSERVED CLIMATE CHANGE

According to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), in recent decades, changes in climate have caused impacts on natural and human systems on all continents and across the oceans. Human influence on climate has been the dominant cause of observed warming since the mid-20th century, while global average surface temperature warmed by 0.85˚C between 1880 and 2012, as reported in the IPCC Fifth Assessment Report, or AR5 (IPCC, 2013; Al-Gamal, 2020). According to the IPCC Special Report in 2018 on the impacts of global warming of 1.5°C, human activities are estimated to have caused approximately 1.0˚C of global warming above pre-industrial levels, with a likely range of 0.8˚C to 1.2˚C. Global warming is likely to reach 1.5˚C between 2030 and 2052 if it continues to increase at the current rate. The observed global mean surface temperature (GMST) for the decade 2006–2015 was 0.87˚C (likely between 0.75˚C and 0.99˚C) higher than the average over the 1850–1900 period (IPCC 2018). In the Northern Hemisphere, 1983–2012 was likely the warmest 30-year period of the last 1400 years (IPCC, 2018).

Most of the problems people have with weather and climate come from extremes. Extreme weather events -- floods, violent storms, droughts and forest fires (Fig. 1) occurred on all inhabited continents in 2019. Annual losses from weather disasters such as hurricanes, hailstorms or wildfires frequently run into hundreds of billions of dollars. In total, weather-related natural disasters have caused the losses of some US$ 4,200bn since 1980 and killed nearly a million people (Munich Re, 2019).

Over the past 100 years, fifteen of the hottest summers have occurred since 2000 and the world is already facing climate change-induced impacts, such as rising sea levels, changing rainfall patterns, increased droughts, and more erratic storms. Furthermore, higher temperatures along with decreased precipitation have been associated with observations of more intense and longer droughts over wider areas since the 1970s. According to IPCC (2013), changes in many extreme weather and climate events have been observed since about 1950. It is very likely that the number of cold days and nights has decreased and the number of warm days and nights has been increased on the global scale. These stresses have exacerbated existing economic, political and humanitarian issues around the world.

El Niño-Southern Oscillation (ENSO) is a recurring cycle that refers to year-to-year variations in sea- surface temperatures, convective rainfall, surface air pressure, and atmospheric circulation that occur across the equatorial Pacific Ocean. The warm phase, in which the central and east-central equatorial Pacific Ocean warms, occurs at intervals of two to seven years (El Niño) and alternates with an opposite cold phase (La Niña) (Guilyardi *et al*., 2009). ENSO is known to affect weather events globally (teleconnection) such as, depending on location, warmer/colder or drier/wetter climate than normal conditions (potential droughts or floods), monsoon rainfall changes, and intensity and frequency of tropical cyclones. El Niño conditions tend to bring slightly lower hurricane activity in the North Atlantic (Tartaglione *et al*., 2003), drier weather in the northern USA and Canada, stronger precipitation in the southern USA and more droughts in southeast Asia and Australia. La Niña has the opposite effect in many cases.

According to Munich Re NatCatService (2020), there was a worldwide increase in natural catastrophes, and proportions of insured losses, in recent decades. About half of the world's population live within 200 km of a coastline, with absolute numbers increasing, and a number of coastal regions are under threat of flooding.

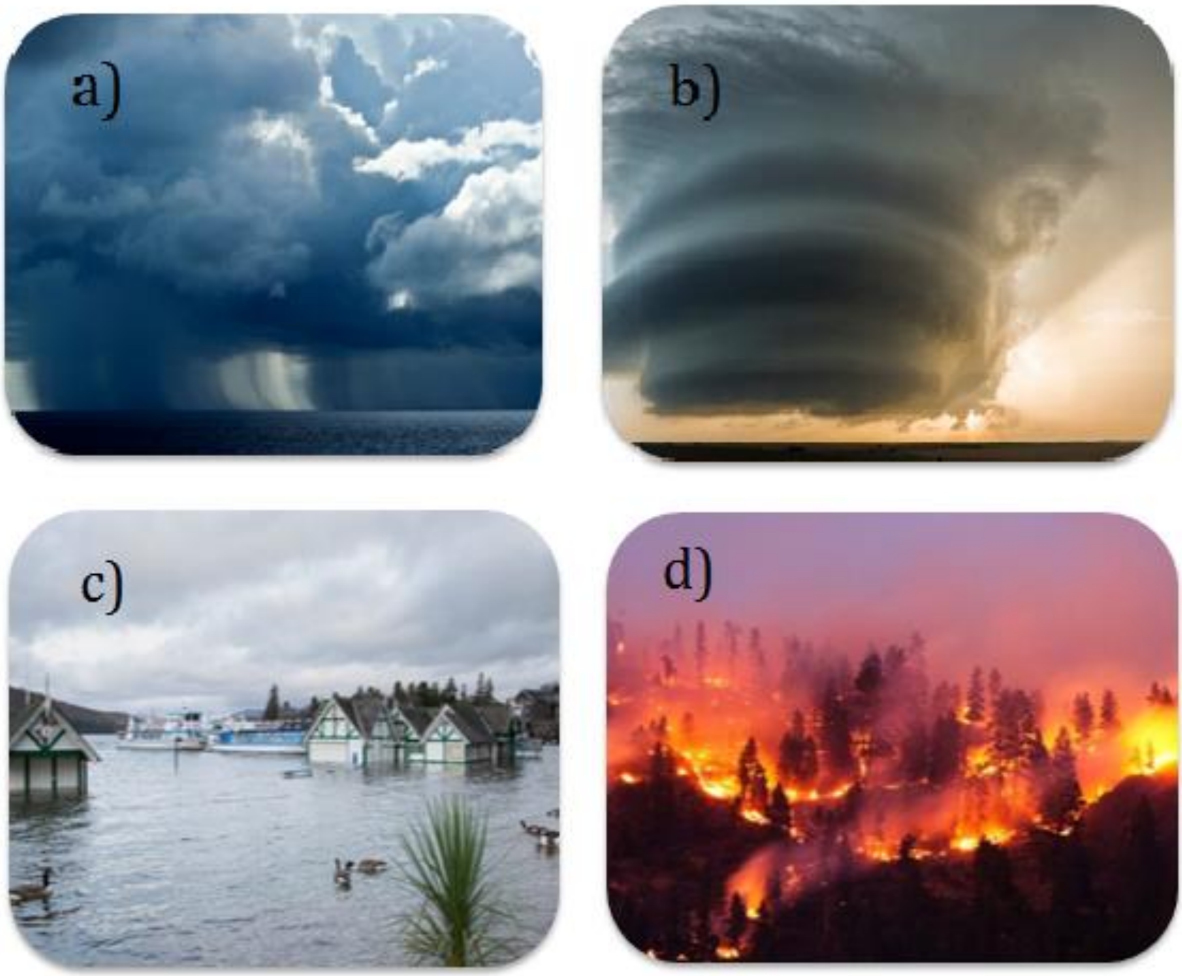

Fig. 1. Extreme weather events: a) Hurricanes, b) Storms, c) Floods, and d) Wild Fires (Munich Re, 2019)

FUTURE CLIMATE CHANGE

Projections of changes in the climate system are made using a hierarchy of climate models ranging from simple climate models, to models of intermediate complexity, to comprehensive climate models, and Earth System Models (IPCC, 2013). These models simulate changes based on a set of scenarios of anthropogenic forcing. In all models, atmospheric CO_2 concentrations are higher in 2100 relative to present day as a result of further increase of cumulative emissions of CO_2 to the atmosphere during the 21st century.

According to IPCC (2013), global surface temperature changes for the end of the 21st century is likely to exceed 1.5˚C relative to 1850 to 1900 for all model scenarios except one. The increase in temperature will be larger on the land than over the ocean and larger than the mean. It will be larger in the Arctic (IPCC, 2014b). There will be more frequent hot temperature extreme episodes over most land areas (IPCC, 2014b). IPCC produced a Special Report in 2018 (IPCC, 2018) on the impacts of global warming of 1.5˚C above pre-industrial levels and related global greenhouse gas emission pathways' contained in the Decision of the 21st Conference of Parties of the United Nations Framework Convention on Climate Change to adopt the Paris Agreement. The report stated that global warming is likely to reach 1.5˚C between 2030 and 2052 if it continues to increase at the current rate (high confidence). An increase in temperature will trigger increased demand for water for evapotranspiration by crops and natural vegetation and will lead to more rapid depletion of soil moisture (FAO, 2013). Climate change is projected to reduce renewable surface water and groundwater significantly in most dry subtropical regions (Jiménez Cisneros *et al*., 2014). This will intensify competition for water use.

Average precipitation will very likely increase in high-latitudes and parts of the mid-latitudes, and the frequency and intensity of heavy precipitation will also likely increase on average. ENSO will very likely continue to be the dominant mode of inter-annual variability in the future (Christensen *et al*., 2013). It is not well understood how ENSO will change in the twenty first century, but the associated precipitation variability on the regional scales is likely to increase due to larger moisture availability in the atmosphere. The contrast in precipitation between wet and dry regions and between wet and dry seasons will increase.

Short-duration precipitation events will shift to more intense individual storms and fewer weak storms are likely as temperature rises. As a result of climate change, freshwater availability increases in regions in the temperate zones but decreases in regions in the low latitudes, including prominent agricultural and heavily irrigated areas in India, China and Egypt (Elbehri and Burfisher, 2015). Constraints on freshwater availability in heavily irrigated areas, however, may lead to large reductions in the irrigated share of overall agricultural production, amplifying direct climate change impacts and increasing weather-induced variability in these regions. Globally averaged, maximum windspeed and rates of precipitation from tropical cyclones will likely increase in the long run (IPCC, 2018). Warming will continue beyond 2100 under all model scenarios. Warming will continue to exhibit interannual-to-decadal variability and will not be regionally uniform.

RESULTS AND DISCUSSION

The global climate crisis is inextricably linked to water. Climate change increases variability in the water cycle, inducing extreme weather events, reducing the predictability of water availability, affecting water quality and threatening sustainable development and biodiversity worldwide.

Climate change is adding significant uncertainty to the availability of water in many regions in the future. It will affect precipitation, runoff and snow/ice melt, with effects on hydrological systems as well as on water quality, water temperature and groundwater recharge. According to the IPCC (2012), there is "medium confidence" that "droughts will intensify in the twenty-first century in some seasons and areas, due to a combination of more variable precipitation and/or increased evapotranspiration". Climate change will also significantly impact sea level with potential impacts on the salinity of surface and groundwater in coastal areas. Mirza (2007) reported that climate change will increase the frequency of floods and droughts in South Asia. It is important to determine the impacts of climate change on water resources in order to develop possible adaptation strategies to improve water productivity.

Agriculture is the sector most vulnerable to climate change due to its high dependence on climate and weather. Climate change and increasing climate variability affect food security in all of its 4 dimensions -- availability, accessibility, utilization and stability (FAO, 2008). Of the total annual crop losses in world agriculture, many are due to direct weather and climatic effects such as droughts, flash floods, untimely rains, frost, hail, and severe storms (Hay, 2007). Chattopadhyay and Lal (2007) estimated that around 28% of the land in India is vulnerable to droughts, 12% to floods and 8% to cyclones. But in the year 1918, which was ranked as the worst drought year of the last century in India, about 68.7% of the total area of the country was affected by drought (Chowdhury *et al*., 1989).

Factors such as climate variability and change contribute to the vulnerability of individual farms, as well as on whole rural communities. More frequent and intense extreme weather events and increasing uncertainty in rainy season patterns are already having significant impacts on food production, food distribution infrastructure, livelihood assets, human health and food emergencies, in both rural and urban areas (FAO, 2008). Galoul *et al*. (2020) described that the impacts of climate change on Southern Mediterranean countries water resources are significant. Climate induced changes in precipitation and air temperature lead to earlier timing of peak flows, greater frequency of flooding, and more extreme drought conditions.

In their article on climate change in South Asia, Sivakumar and Stefanski (2011) enlisted the following climate change impacts in South Asia: impacts of enhanced temperatures; impacts of precipitation variability and water resources; impacts of increased frequency of extreme events and natural disasters; impacts of crop, pasture and forest productivity; impacts on crop pests and diseases; impacts on fisheries; and impacts of sea level rise.

In its broadest sense, water productivity (WP) is the net return for a unit of water used. Water availability issues include how much water can be diverted, when the water can be available and how much water can be stored in surface and ground-water reservoirs. Issues of global water availability and scarcity have been considered in a variety of ways, including identifying areas of water availability (Oki and Kanae, 2006), water stress (Wada *et al*., 2011), impacts of water use (Pfister *et al*., 2009), and projections of future water scarcity (Murray *et al*., 2012).

Crop production is the largest global consumer of freshwater, and water is a key resource in food production. Crop water productivity is defined here as food (edible) kilocalories produced per litre of evapotranspiration, evaluated separately for rainfed and irrigated crops (Brauman *et al*., 2013). Water consumption by crops varies substantially across the globe, reflecting differences in cropping density, crop choice, soil characteristics, irrigation availability, and agricultural management as well as climatic drivers of evapotranspiration. Because climate is central to physical crop water productivity, climate change brings about a further uncertainty to the scope for increasing water productivity.

The water productivity concept evolved from separate fields. Crop physiologists originally defined water use efficiency as carbon assimilated and crop yield per unit of transpiration (Viets, 1962), and then later as the amount of produce (biomass or marketable yield) per unit of evapotranspiration (ET). Irrigation specialists have used the term water use efficiency to describe how effectively water is delivered to crops and to indicate the amount of water wasted. Gains in water productivity will be substantially offset by increased temperature (Long *et al*., 2006).

STRATEGIES TO IMPROVE WATER PRODUCTIVITY

Increasing water productivity is particularly appropriate where water is scarce compared with other resources involved in production. The scope for improvement remains in many rainfed, irrigated, livestock and fisheries systems in many regions of the world.

Reasons to improve agricultural water productivity include: (i) to meet rising demands for food from a growing, wealthier, and increasingly urbanized population in light of water scarcity, (ii) to respond to pressures to re-allocate water from agriculture to cities and ensure that water is available for environmental uses, and (iii) to contribute to poverty reduction and economic growth (Molden *et al*., 2009). For the rural poor, more productive use of water can mean better nutrition for families, more income and productive employment. The strategies to improve water productivity are described below:

Implementation of improved policies

There are gains to be made in water productivity, but these will require the policies and actions that recognize the complex nature of achieving those gains. In the light of the uncertainties of climate variability, water demand and socio-economic environmental effects, it is urgent to take some measures to use the limited water efficiently and develop some new water resources. Khan (2008) discussed climate variability and droughts in Australia according to historical climate data and suggested some possible policy approaches to adjust water allocations of surface and groundwater using prediction models, to improve the water use efficiency in agriculture and to build a national legal framework to manage water resources in accordance with anticipated climate change impacts on water resources.

Many factors outside the water sector must also be considered in efforts to improve water productivity. These include changing prices for agricultural commodities, increasing demand for biofuels, urbanization and changing diets with a rising population (de Fraiture *et al*., 2008; Molden *et al*., 2007a,b). Policies influencing these drivers will also influence water use, and thereby influence the scope for gains in water productivity. While some factors, such as the recent increase in commodity prices may make investments in water productivity attractive, there is a high degree of uncertainty as to how these will impact water productivity in the future.

Emphasis on sustainability

The term sustainable development was coined in the paper Our Common Future which was published by the the United Nations World Commission on Environment and Development (UNWCED, 1987). Sustainable development was defined as "development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs".

In September 2015, international community endorsed a universal agenda entitled 'Transforming our World: the 2030 Agenda for Sustainable Development', known as the Sustainable Development Goals (SDGs). The 17 goals and 169 targets to be met by 2030 were developed with widespread participation and were adopted in 2012 for the overarching goals of sustaining people, prosperity, peace, partnerships and the planet. The preamble to the SDGs announces 'to take the bold and transformative steps which are urgently needed to shift the world onto a sustainable and resilient path' (UNRISD, 2016).

SDG 6 focusses on ensuring availability and sustainable management of water and sanitation for all. The theme of World Water Day, on 22 March 2020 focussed on 'Water and Climate Change' which explores how water and climate change are inextricably linked. The World Water Day 2020 campaign explains statements such as:

- We cannot afford to wait. Climate policy makers must put water at the heart of action plans.
- Water can help fight climate change. There are sustainable, affordable and scalable water and sanitation solutions.
- Everyone has a role to play. In our daily lives, there are surprisingly easy steps we can all take to address climate change.

NATIONAL AND REGIONAL CLIMATE POLICY AND PLANNING MUST TAKE AN INTEGRATED APPROACH TO CLIMATE CHANGE AND WATER MANAGEMENT

Focus on priority areas

According to Molden *et al*. (2009), priority areas where substantive increases in water productivity are possible include: (i) areas where poverty is high and water productivity is low, (ii) areas of physical water scarcity where competition for water is high, (iii) areas with little water resources development where high returns from a little extra water use can make a big difference, and (iv) areas of water-driven ecosystem degradation, such as falling groundwater tables, and river desiccation. However, achieving these gains will be challenging at least, and will require strategies that consider complex biophysical and socioeconomic factors.

Improving water resources management

It is necessary to develop optimal water management practices based on climatic conditions to avoid overuse of water resources, mitigate groundwater table decline and maintain a sustainable agricultural production. This requires knowledge of how crop yield, water productivity (WP) and water balance are influenced by climate variability and irrigation management (Chen *et al*., 2010). According to Govindarajan *et al*. (2008), water productivity concerned with water saving irrigation is dependent on the groundwater level and evapotranspiration.

FAO (2016) identified broad adaptation themes to changing rainfall, water availability and extreme weather conditions at the farm level (Table 1). These adaptation practices at farm level can be complemented and supported by measures in other sectors, such as agricultural R & D and innovation, and at landscape levels.

Judicious use of water using supplementary irrigation systems, more efficient irrigation practices, and the adaptation and adoption of existing and new water harvesting technologies have been suggested as appropriate strategies (FAO, 2007).

Examples of interventions that have demonstrated improvements in water productivity include: rainwater harvesting and local water storage, applying drip or deficit irrigation, adjusting planting dates, and modifying tillage practices to reduce evaporation (Zwart *et al*., 2010; Ali and Talukder 2008; Hatfield *et al*., 2001).

Guo *et al*. (2002) studied the climate change impacts on the runoff and water resources with the GIS (geographic information system) and GCMs in China and pointed out that runoff is more sensitive to precipitation variation than to temperature increase, and integrated water resources management can help mitigate climate change.

Table 1. Options for adaptation to changing rainfall, water availability and extreme weather conditions at the farm level (FAO, 2016)

Risk	Response
Change in rainfall and water availability	Participate in monitoring schemes when available. Change irrigation practices. Adopt enhanced water conservation measures. Use marginal and waste water resources. Make more use of rainwater harvesting and capture. In some areas, increased precipitation may allow irrigated or rain-fed agriculture in places where previously it was not possible. Alter agronomic practices. Reduced tillage to lessen water loss, similarly the incorporation of manures and compost, and other land use techniques such as cover cropping increase soil organic matter and hence improve water retention.
Increased frequencies of droughts, storms, floods, wildfire events, sea level rise	Participate in monitoring schemes with available General water conservation measures are particularly valuable at times of drought. Use flood, drought and/or saline resistant varieties. Improved drainage, improved soil organic matter content and farm design to avoid soil loss and gullying. Consider (where possible) increasing insurance cover against extreme events.

According to Molden *et al*. (2009), there is considerable scope for improving water productivity of crop, livestock and fisheries at field through to basin scale. Practices used to achieve this include water harvesting, supplemental irrigation, deficit irrigation, precision irrigation techniques and soil–water conservation practices. Practices not directly related to water management impact water productivity because of interactive effects such as those derived from improvements in soil fertility, pest and disease control, crop selection or access to better markets.

According to Chen *et al*. (2010), water productivities of wheat and maize under no irrigation were low and varied greatly. The average of wheat water productivity reached maximum value under the two-irrigation treatments and declined under three and four irrigations.

Li and Barker (2004) found that the AWD (alternate wetting and drying) irrigation technique can increase water productivity for paddy irrigation in China.

Efficient water use and integrated management will be increasingly important for reducing the impacts on water scarcity and droughts and for managing future water resource conditions.

Use of appropriate models

Agricultural system models have been proven to be useful tools to investigate the potential impacts of climate variability on crop productivity (Asseng *et al*., 1997) and field water balance (Keating *et al*., 2002), and how crop yield responds to water management strategies (Mo *et al*., 2005).

Wurbs *et al*. (2005) provided a water availability modelling (WAM) system to assess the water supply capabilities and explore the climate impacts on hydrology and water availability for water users who depend on water supplies by the Brazos River Basin in Texas, and the key result is that future climate may decrease the mean streamflow, and its effects on water availability are various in different regions of the river basin.

Cuculeanu *et al*. (2002) used the VIDRA rainfall runoff model to discuss climate vulnerability impacts on water resources in 2075 in Romania, and the conclusion is that water requirements in the reference basin will exceed water availability.

Quinn *et al*. (2001) discussed an integrated system to analyze the impacts of climate variability on water resources in the San Joaquin Basin, California, the conclusion is that this method can provide a reference for effective management strategies to assess the climate vulnerability as a function of climate variability and extreme events.

Soil water balance is important for the water management and water use strategy. Eitzinger *et al.* (2003) used the CERES-wheat model to assess climate change impacts on soil water balance under four climate scenarios, and the results show that the factors which affect the soil water balance also have influences on the sustainable crop production and water resources in agriculture.

Enhancing livestock productivity

There is considerable scope for increases in livestock productivity, in both physical and economic water productivity. Strategies to enhance water productivity include improving feed sourcing of animals, enhancing animal production (milk, meat, eggs), improving health through veterinary services, grazing practices that avoid land degradation to lessen the amount of water required for grazing and reduce negative environmental impacts such as erosion (Peden *et al.,* 2007). Livestock generate numerous values beyond food production that should be taken into account, including transport, plowing, support of cultural values and a means of buffering against drought.

Focus on fisheries and aquaculture

As with livestock, there is considerable scope for better integration of fisheries and aquaculture with water management systems to improve the water productivity. The two major components of water use in aquaculture are the water required to produce feed and the blue water required for aquaculture. Water productivity is the mass or value of the aquaculture produce divided by the amount of water required for feed plus the amount of evaporation from the pond.

CONCLUSION

There are many vulnerable regions in the world to climate change in view of the high population and the large number of communities facing food insecurity. There will be substantial impacts on the water resources in terms of scarcity (drought) and abundance (flooding). Urgent steps are needed to increase the water productivity to face current as well as future climate risks. There is considerable scope to improve water productivity in many rainfed, irrigated, livestock and fisheries systems in many regions of the world. The strategies to improve the water productivity will need to simultaneously consider implementation of appropriate policies, improved water management and sustainable development. Regular dialogue with the user communities could help identify the important needs and opportunities to help the user communities to effectively deal with climate change impacts and enhance the water productivity.

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